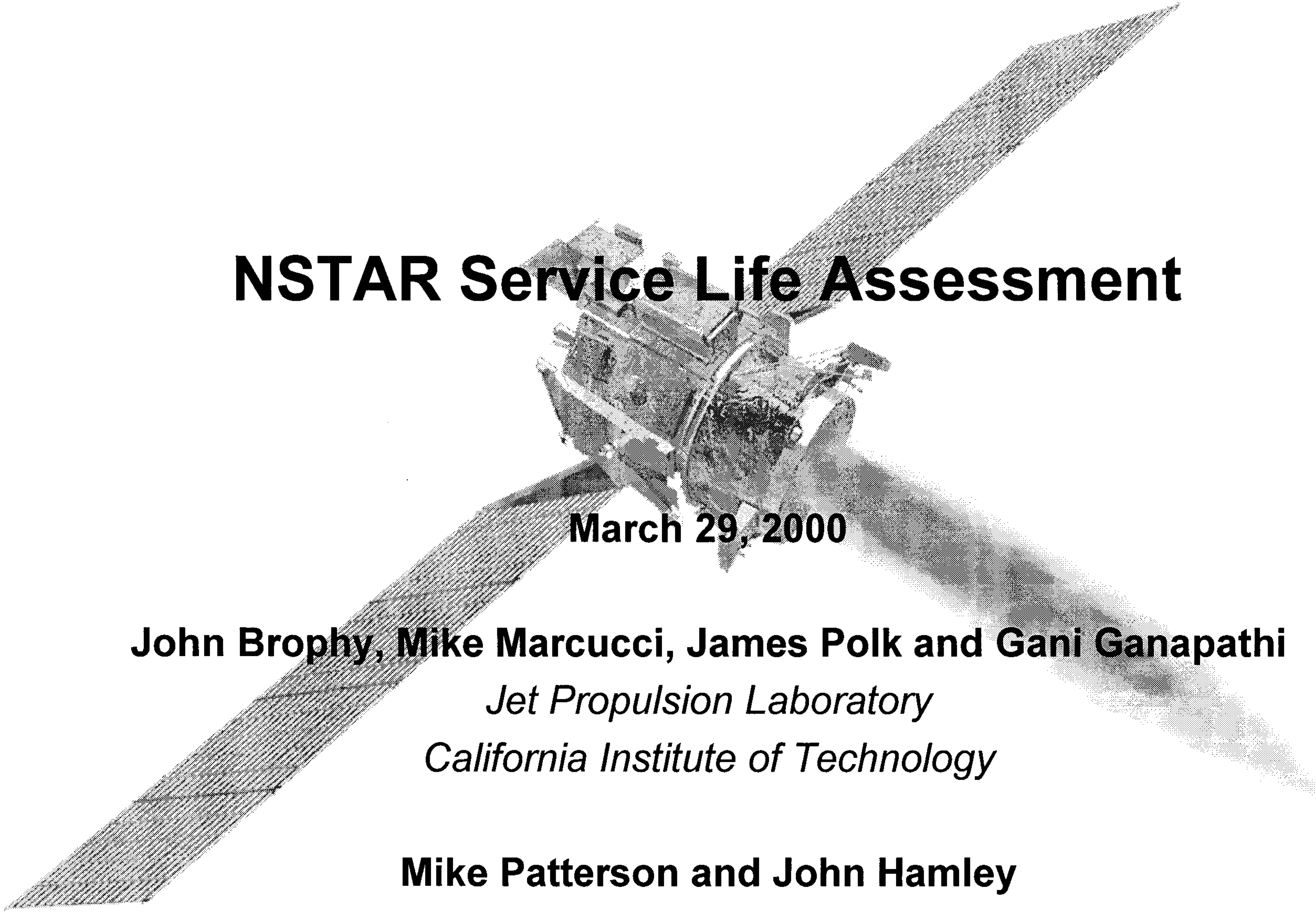

NSTAR Service Life Assessment

March 29, 2000

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California Institute of Technology

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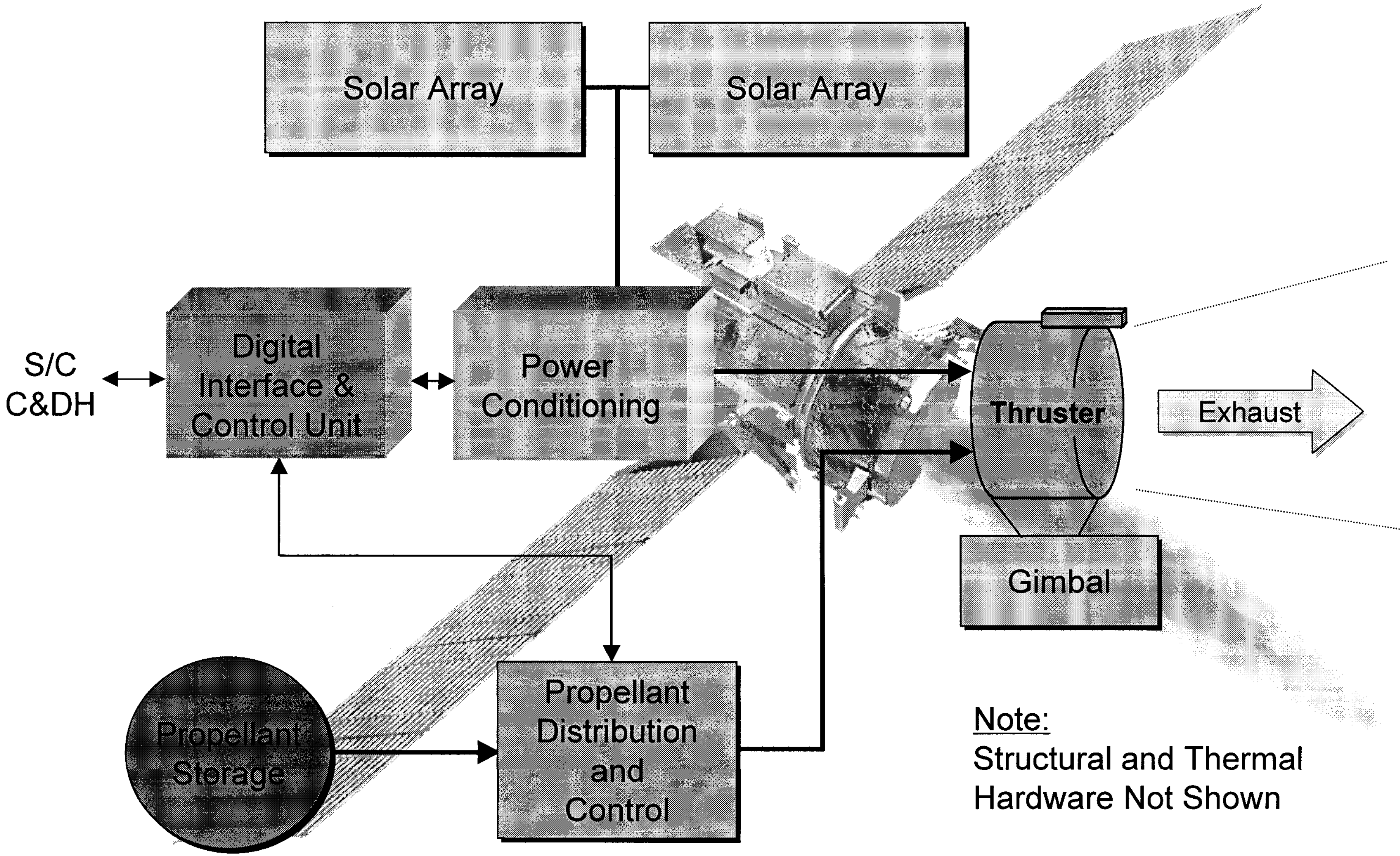
Glenn Research Center

Purpose of this Briefing

- **Present results of flight validation and ground testing of the NSTAR SEP system service life**
  - Results of Peer-Review at JPL by GRC, MSFC and JPL Personnel

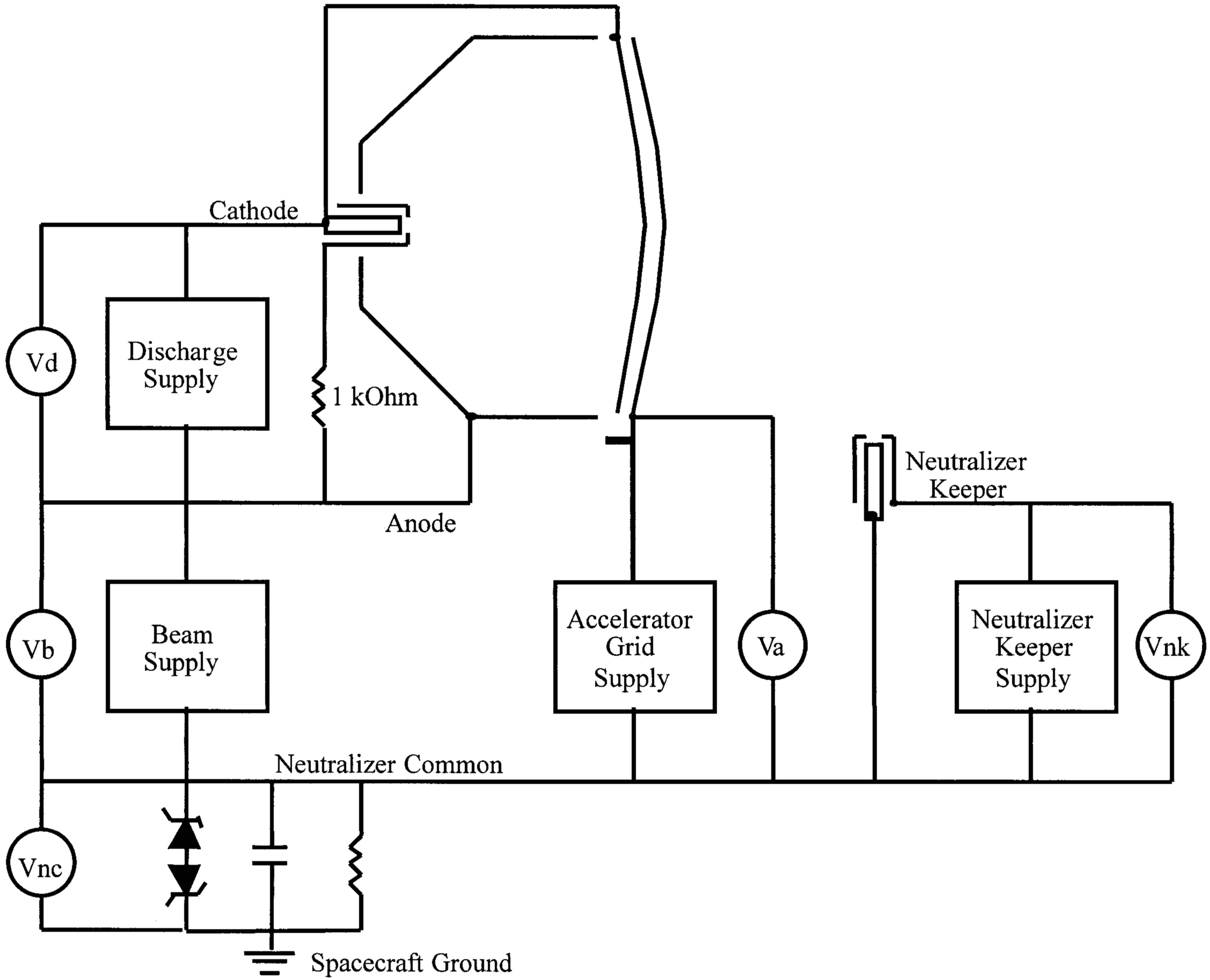
- *Recommend to NASA that the service life of the NSTAR ion engine is a xenon throughput of 130 kg*

SEP/NSTAR System Elements



Note:
Structural and Thermal Hardware Not Shown

Ion Engine Operation



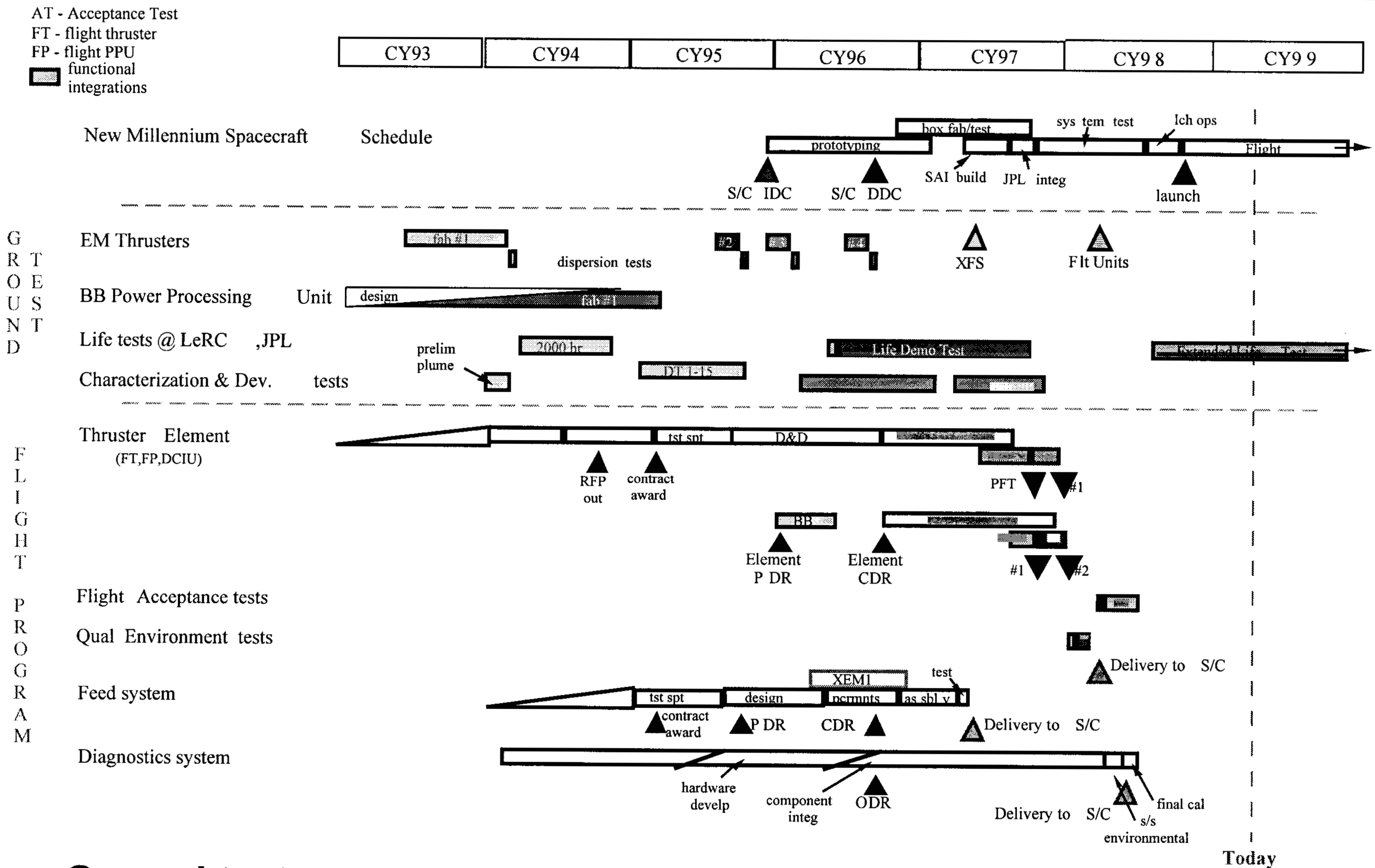
NSTAR Technology Validation Goals

➊ ***Demonstrate that the NASA 30-cm diameter ion engine has sufficient service life to perform missions of near-term interest***

➋ **Demonstrate through a flight test that the ion propulsion system hardware and software could be flight qualified and successfully operated in space, and demonstrate control and navigation of an SEP spacecraft**

➌ **Understand the interactions between the Ion Propulsion System and the spacecraft**

NSTAR Project Schedule



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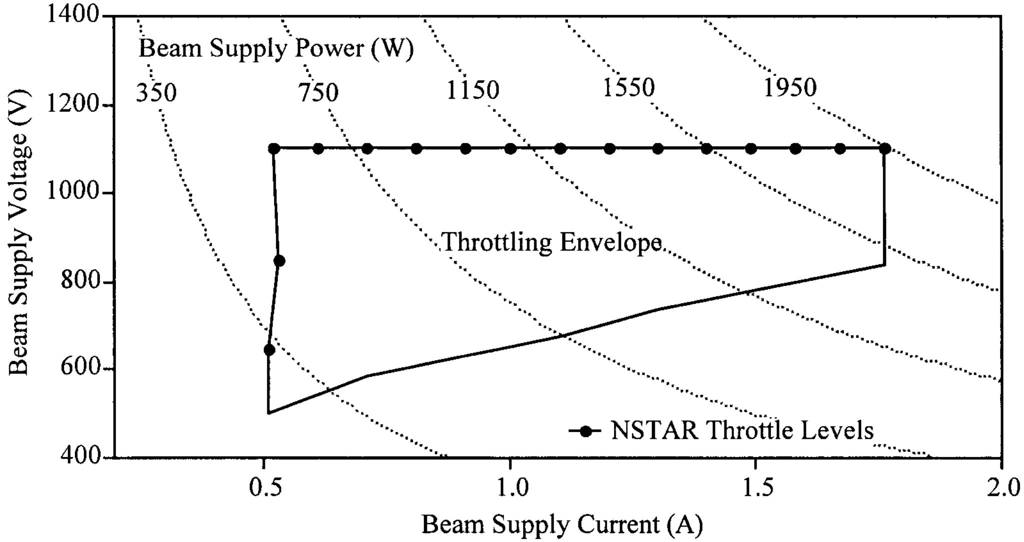
- **Ground test program more extensive than the original plan**
  - 13,780 total test hours on 4 EM thrusters
  - 12,245 flight thruster hours (and counting)

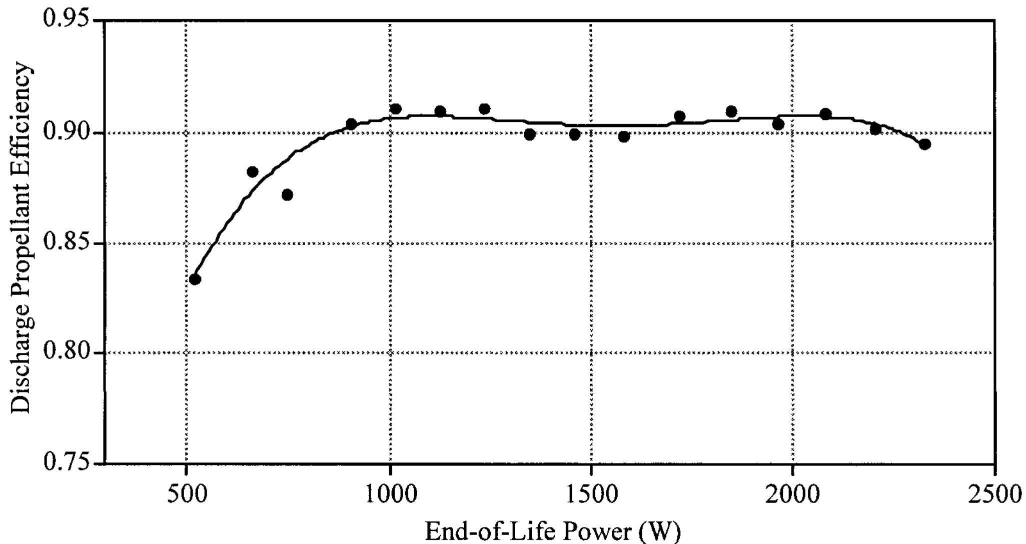
What We Learned From the Flight on Deep Space 1 (after 3,575 hours of thrusting)

Thruster Operation In Space is the Same as on the Ground

- Thruster performance in space agrees very well with ground test data
- Ion optics behavior in space agrees very well with ground-test data
- Accelerator grid impingement currents are slightly lower (i.e. better) than ground measurements
- Recycle rate is lower (i.e., better) in space
- Discharge voltage the same or lower (i.e. better) in space
- Neutralizer keeper voltage is lower (i.e. better) in space

The NSTAR Throttling Strategy





- **NSTAR uses a maximum Isp throttling profile**
- **Propellant utilization efficiency is a compromise between engine efficiency and engine life**
- ***The 130-kg throughput service life is applicable to all throttling profiles which have an average engine input power of $\leq$ 2.14 kW***

NSTAR

NSTAR EOL Throttle Table

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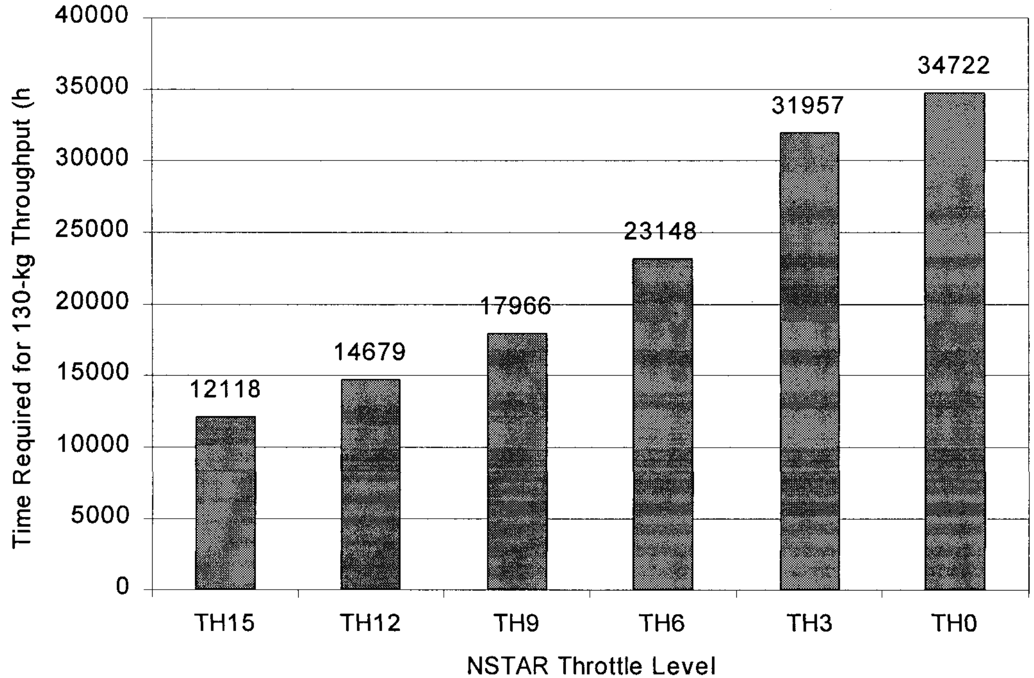
NSTAR Throttle Level	Mission Throttle Level	PPU Input Power (kW)	Engine Input Power (kW)	Calculated Thrust (mN)	Main Flow Rate (sccm)	Cathode Flow Rate (sccm)	Neutralizer Flow Rate (sccm)	Specific Impulse (s)	Total Thruster Efficiency
15	111	2.567	2.325	92.67	23.43	3.70	3.59	3127	0.618
14	104	2.416	2.200	87.87	22.19	3.35	3.25	3164	0.624
13	97	2.272	2.077	83.08	20.95	3.06	2.97	3192	0.630
12	90	2.137	1.960	78.39	19.86	2.89	2.80	3181	0.628
11	83	2.006	1.845	73.60	18.51	2.72	2.64	3196	0.631
10	76	1.842	1.717	68.37	17.22	2.56	2.48	3184	0.626
9	69	1.712	1.579	63.17	15.98	2.47	2.39	3142	0.618
8	62	1.579	1.456	57.90	14.41	2.47	2.39	3115	0.611
7	55	1.458	1.344	52.67	12.90	2.47	2.39	3074	0.596
6	48	1.345	1.238	47.87	11.33	2.47	2.39	3065	0.590
5	41	1.222	1.123	42.61	9.82	2.47	2.39	3009	0.574
4	34	1.111	1.018	37.35	8.30	2.47	2.39	2942	0.554
3	27	0.994	0.908	32.12	6.85	2.47	2.39	2843	0.527
2	20	0.825	0.749	27.47	5.77	2.47	2.39	2678	0.487
1	13	0.729	0.659	24.55	5.82	2.47	2.39	2382	0.472
0	6	0.577	0.518	20.69	5.98	2.47	2.39	1979	0.420



Identifying Potential Failure Modes is Critical

- **Launch vehicle experience shows most failure modes are due to :**
  - Unknown causes
  - Previously unrecognized failure modes
  - Poorly-understood failure modes
  - Manufacturing errors that affect known failure modes

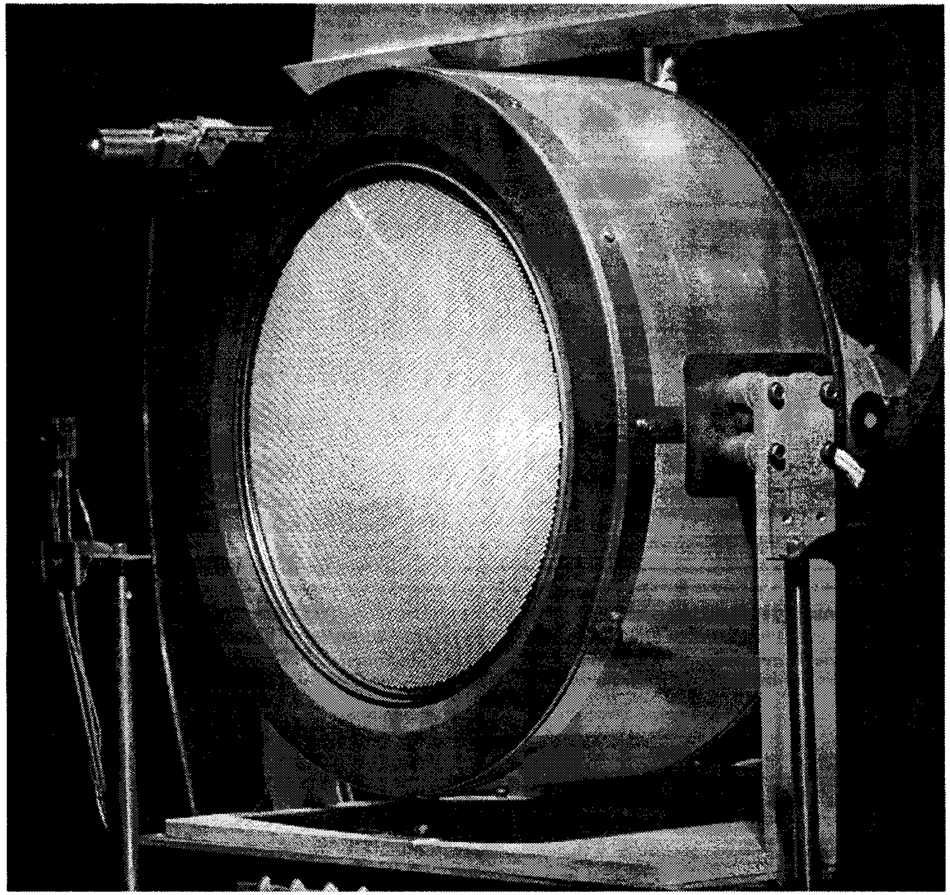
- **Event-consequent failures result from the improper fabrication and/or operation of a component**
  - We are assuming that fabrication related failures are identified and corrected by inspection and testing of the flight hardware as was done successfully for DS1
  - Failures due to improper component operation are assumed to be eliminated through implementation of the NSTAR specifications

• There is no way to control the risk from unknown failure modes

• *Therefore identifying the critical failure modes is of utmost importance!*

NSTAR — Methods for Identifying Wear-Out Failure Modes

- **Testing**
  - 13,780 total test hours on 4 EM thrusters
    - 8,192 hrs on one thruster (88-kg throughput)
  - 12,800 flight thruster hours (and counting)
    - 9,300 hrs on FT2
    - 3,500 hrs in flight (FT1)
  - 99,562 hours of cathode testing
- **Long-Duration Testing Used To:**
  - Identify failure modes
  - Characterize the environment and loads that drive failure modes
  - Anchor models used in the analyses
  - Characterize performance variation vs. propellant throughput
- **Experience**
  - Failure modes observed in 65 previous endurance tests
  - Plasma contactor experience
  - Hughes experience



There is a vast body of experimental data on ion engine testing -- it would be very unlikely, based on this experimental experience to find an unknown failure mode for the NSTAR operating conditions

Top 10 List of Engine Wear-Out Failure Modes

① Electron-backstreaming due to enlargement of the accelerator grid apertures by ion sputtering

② Structural failure of the accelerator grid by charge-exchange ion erosion

③ Structural failure of the screen grid due to ion sputtering

④ Unclearable short between the screen and accelerator grids by one or more flakes of sputter-deposited material

⑤ Cathode insert failure

⑥ Rogue hole formation resulting in electron-backstreaming or structural failure of the accelerator grid

⑦ Keeper orifice plate structural failure of the due to ion sputtering

⑧ Neutralizer orifice plate erosion due to plume mode operation

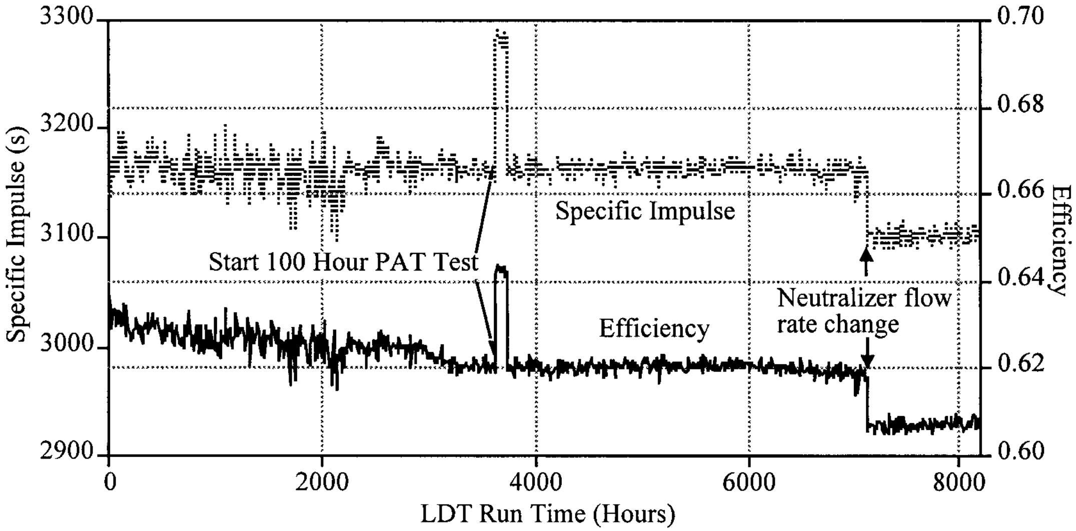
⑨ Cathode heater failure due to thermal cycling

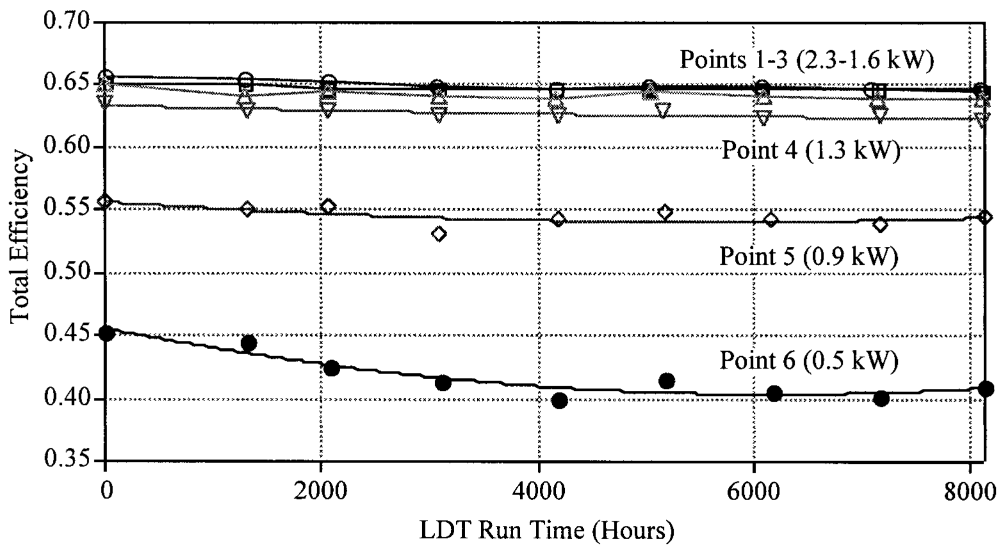
⑩ Unclearable short between the cathode and the keeper electrode (soft failure)

What We Learned From the NSTAR Ion Engine Endurance Testing

NSTAR

Thruster Performance was Excellent Over the 8,200-hr Test





- ***Very Little Performance Change After the First 4,000 hours (44 kg throughput)***
- ***Isp constant after first 4,000 hours*, except where flows have changed**
- **Low power point performance loss is more significant**

NSTAR — Discharge Behavior was Outstanding Over the 8,200-hr Test

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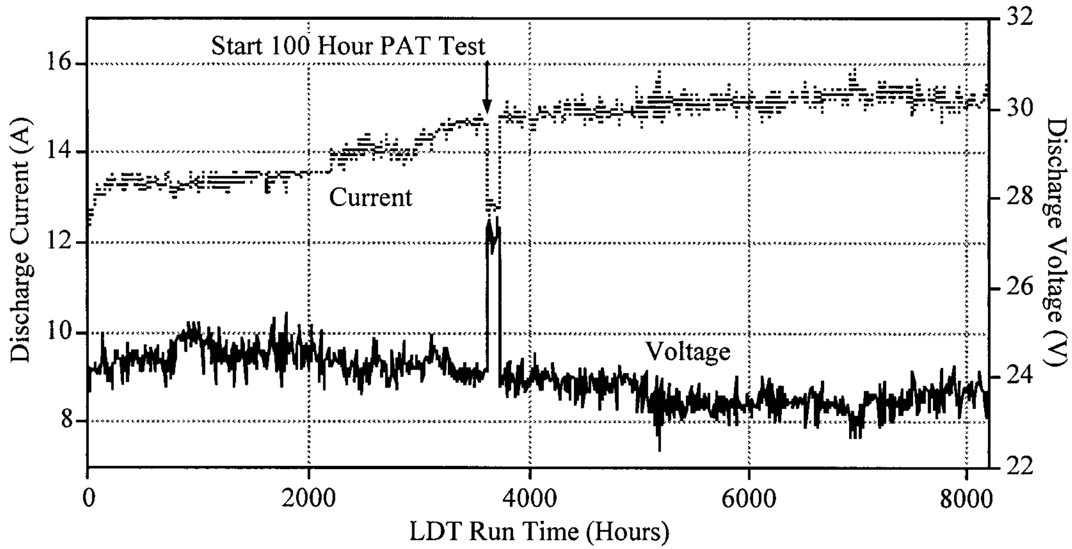

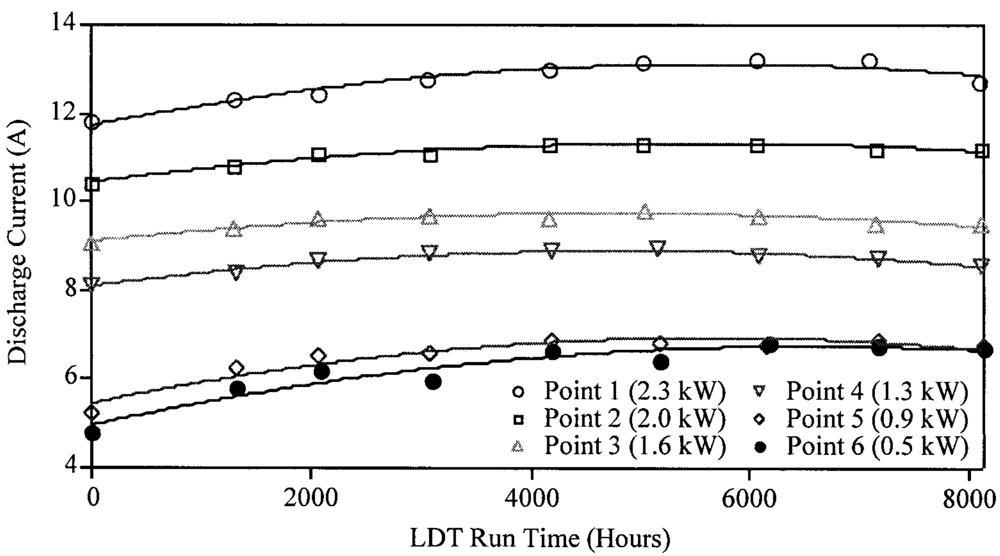

- ***Discharge voltage is remarkably low -- results in long engine life***
- **Discharge current increases with time at all throttle levels due to grid wear**
- ***Component electrical isolation was good for entire test***

Failure Modes

① **Electron-backstreaming due to enlargement of the accelerator grid apertures by ion sputtering**

② **Structural failure of the accelerator grid by charge-exchange ion erosion**

NSTAR

Failure Mode 1
Electron-Backstreaming

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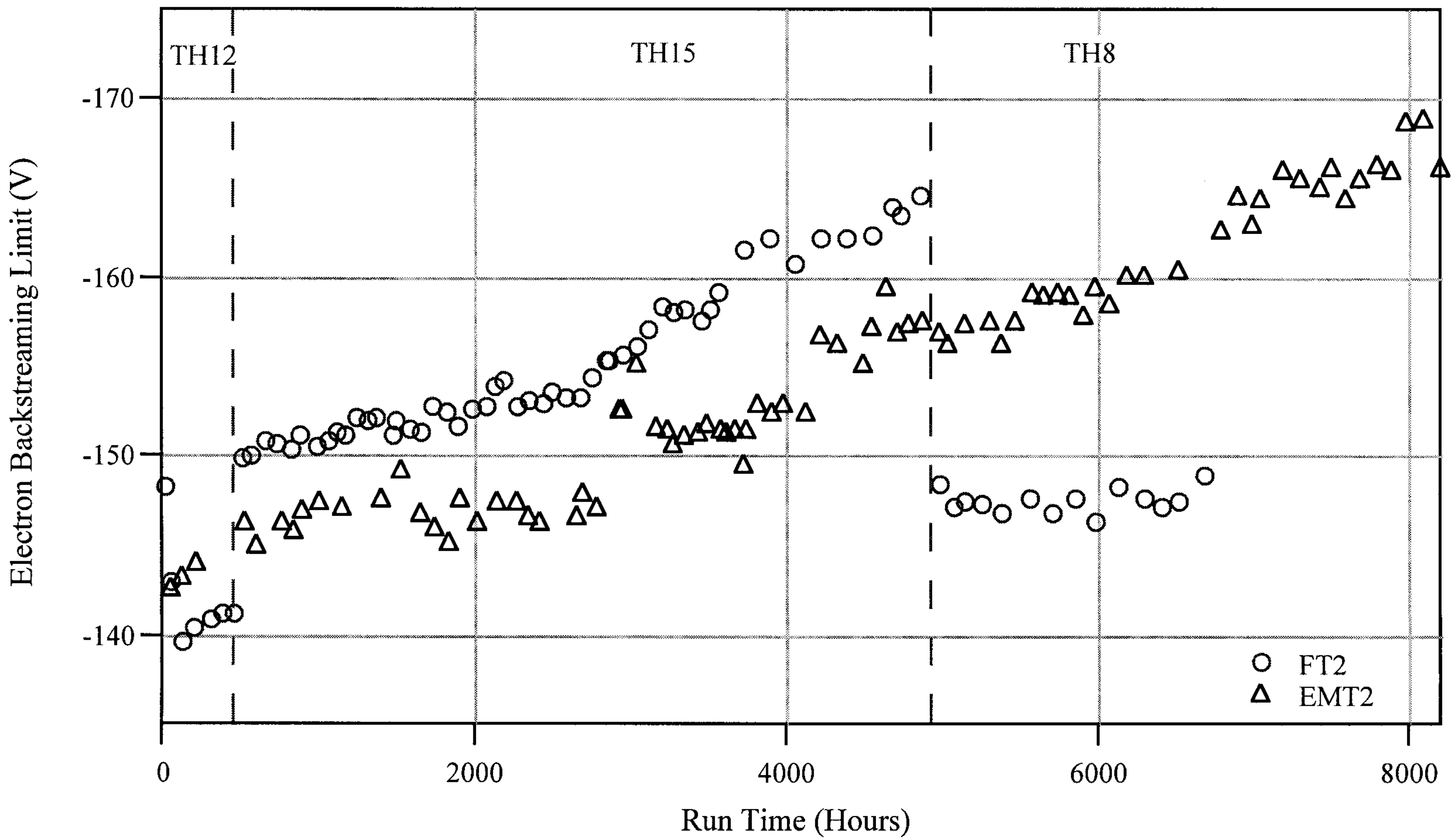
- The Flight Spare Thruster behaves like the Engineering Model Thruster (Magnitude Difference Reflects a Slight Difference in Grid Separation)



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Combined Failure Modes 1 & 2
Accelerator Grid Failure

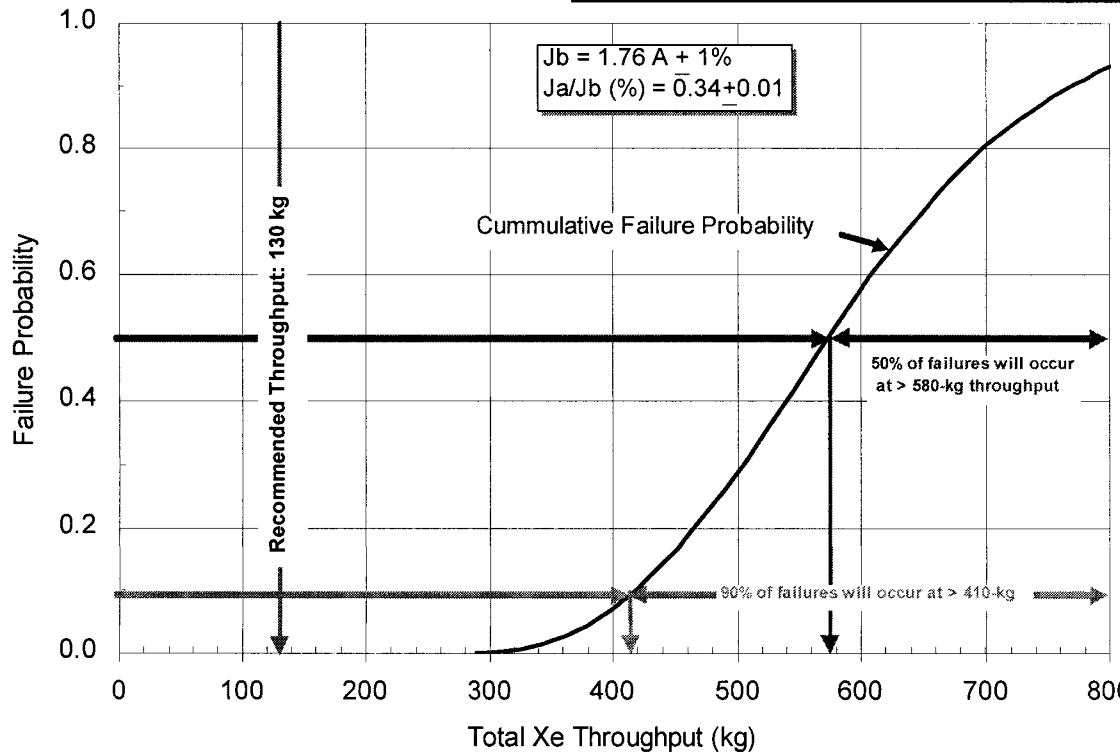
Symbol	Definition	Values
A_b	Active grid area [m2]	0.06587
e	Electron charge [coul.]	1.6×10^{-19}
f_a	Accelerator grid mass loss flatness parameter	0.41 to 0.61
J_b	Beam Curent [A]	$1.76 \pm 1\%$
m_g	Mass of screen grid atom [kg]	1.59×10^{-25}
V_a	Accelerator grid voltage [V]	180 to 250
V_{bp}	Ion beam plasma potential [V]	4 to 10
V_g	Neutralizer coupling voltage [V]	11 to 15
V_i	Ion energy for sputter-yield calculation [V]	$= V_a + V_g + V_{bp}$
t_a	Accelerator grid thickness [m]	5.08×10^{-4}
Y	Sputter yield at mormal incidence [atoms/ion]	$= -0.1935 + 2.622\times10^{-3}V_i - 9.97\times10^{-7}V_i^2$
α	Eroded area fraction	$= 0.12525 + (0.53973 w_g \times 10^3)$
α_a	Accelerator grid current to beam current ratio	0.35
β	Fraction of accelerator grid current striking the pits & grooves erosion pattern	0.7 to 0.8
λ_{pg}	Sputter yield parameter for pits & grooves erosion	$0.081/\beta$ to $0.286/\beta$
ϕ_a	Accelerator grid open area fraction	0.24
w_g	Width of the pits & grooves erosion pattern at the center of the grids [m]	4.50×10^{-4} to 5.75×10^{-4}

Symbol	Definition	Values
d_0	Accelerator grid hole diameter after the cusp has been removed [m]	1.27×10^{-3}
l_g	Screen-Accelerator grid gap [m]	5.9×10^{-4} to 6.6×10^{-4}
N_h	Number of holes in the accelerator grid	15,400
T	Run Time [s]	
λ_h	Sputter yield parameter for hole erosion	0.5 to 1.0
ρ	Density of accelerator grid material [kg/m³]	10220

$$T_{ag} = \frac{A_b(1-\phi_a)\alpha\, f_a e \rho\, t_a}{J_b \alpha_a\, \beta\, Y \lambda_{pg} m_g}$$

$$T_{eb} = \left(D^2 - d_0^2\right)\left(\frac{\pi\rho\, t_a e f_a N_h}{4 J_b \alpha_a Y m_g (1-\beta)\lambda_h}\right)$$

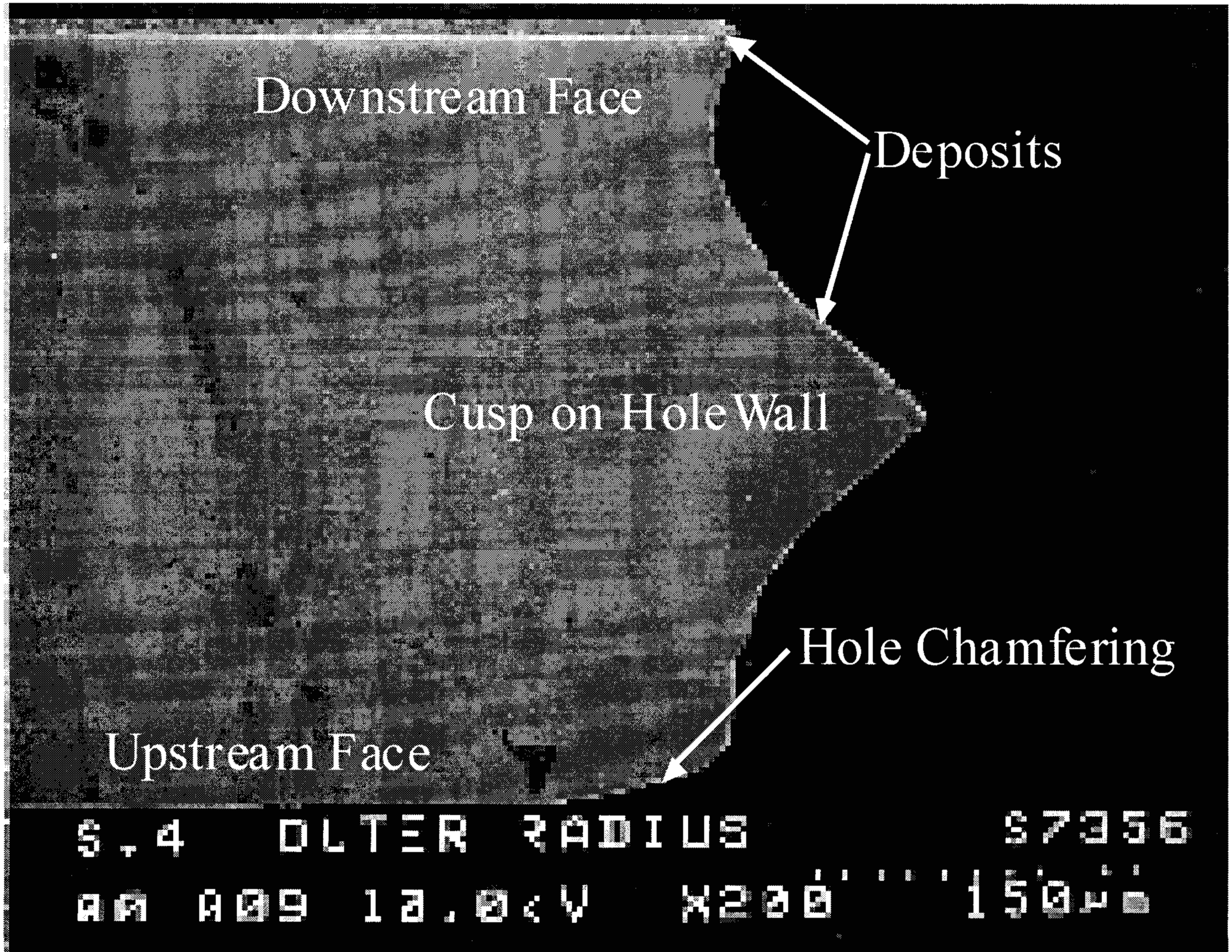
At 130-kg Throughput the Accelerator grid has a factor of 3.1 margin before the failure risk reaches 10%



Failure Mode 3
Wear and Deposition Sites on the Screen Grid

NSTAR

③ Structural failure of the screen grid due to ion sputtering



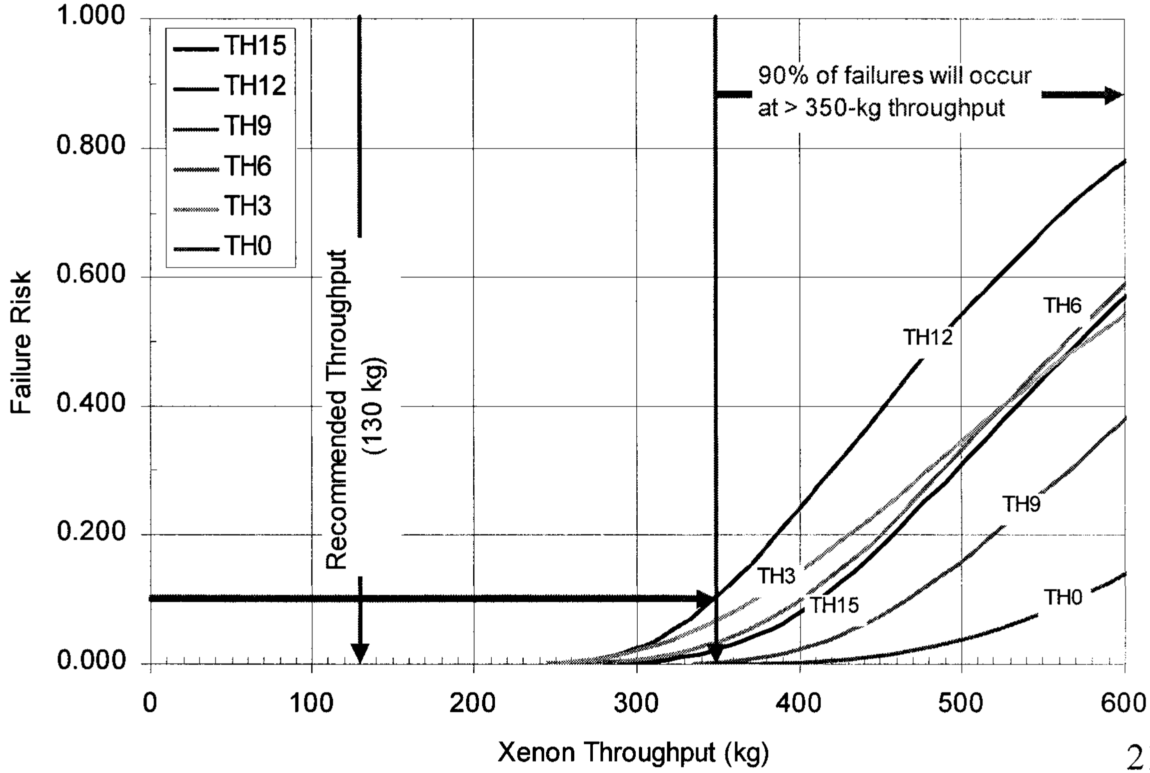
> *There is essentially **no erosion** on the screen grid after 8,200 hours of operation (88 kg throughput)*

Failure Mode 3
Screen Grid Erosion

Symbol	Definition	Values
A_b	Active grid area [m2]	0.06587
e	Electron charge [coul.]	1.6×10^{-19}
f_b	Beam current flatness parameter	0.40 to 0.46
f_d	Double ion ratio correction to centerline parameter	1.40 to 1.67
J_b	Beam Curent [A]	$1.76 \pm 1\%$
m_g	Mass of screen grid atom [kg]	1.59×10^{-25}
R_+^{++}	Measured double to single ion current ratio	0.15 to 0.20
t_s	Screen grid thickness [m]	3.80×10^{-4}
V_d	Discharge voltage [V]	24.5 to 26.0
Y_+	Single ion sputter yield = $1.06\times10^{-5} + (V_d-24.8)^2$ [atoms/ion]	$\pm50\%$
Y_{++}	Double ion sputter yield = $1.06\times10^{-5} + (2V_d-24.8)^2$ [atoms/ion]	$\pm50\%$
ρ	Density of screen grid material [kg/m3]	10220
ϕ_i	Screen grid transparency to ions	0.82
ϕ_s	Screen grid open area fraction	0.67

$$T_{sg} = \frac{t_s \phi_i f_b e \rho\, A_b (1-\phi_s)(1+f_d R_+^{++})}{J_b m_g (1-\phi_i)\left(Y_+ + \frac{f_d}{2} R_+^{++} Y_{++}\right)}$$

At 130-kg Throughput the Screen grid has a factor of 2.7 margin before the failure risk reaches 10%



NSTAR

Failure Modes 4 & 6
Discharge Chamber After 8.2-khr Test is Remarkably Flake Free

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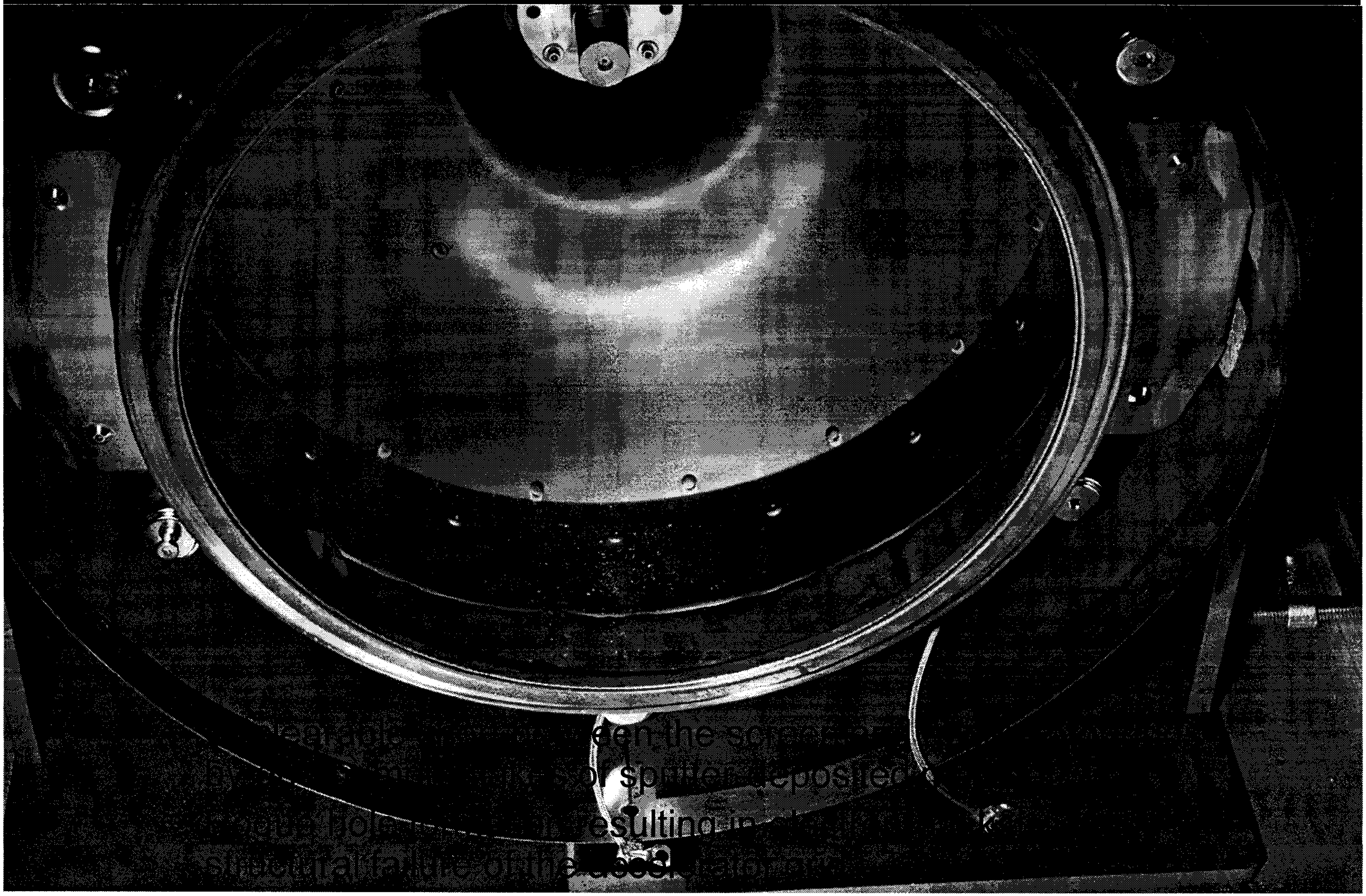
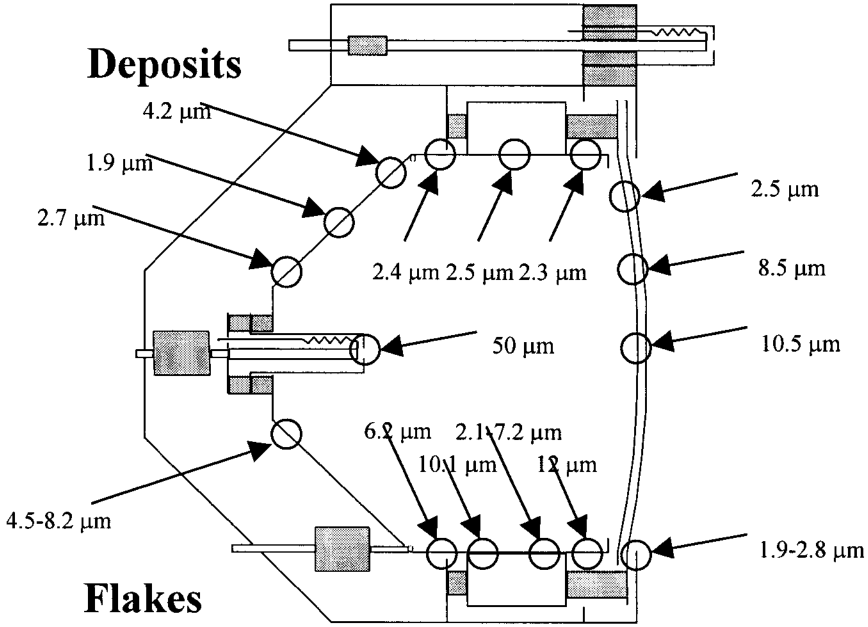
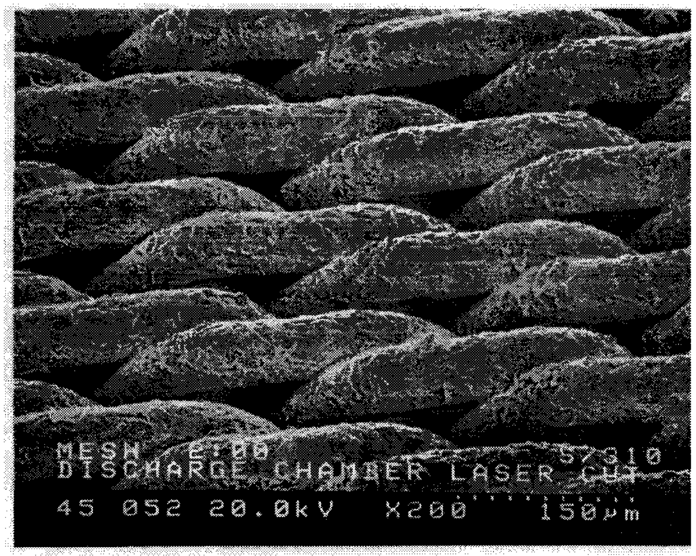


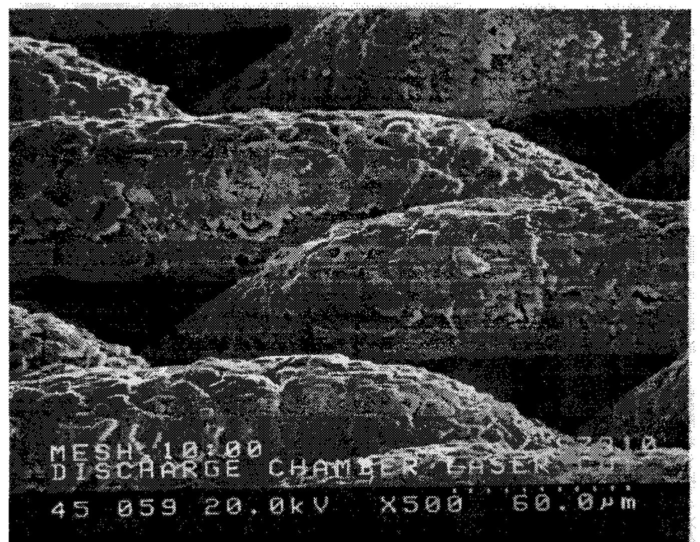
NSTAR

Failure Modes 4 & 6
Deposit and Flake Thicknesses





MESH 2:00

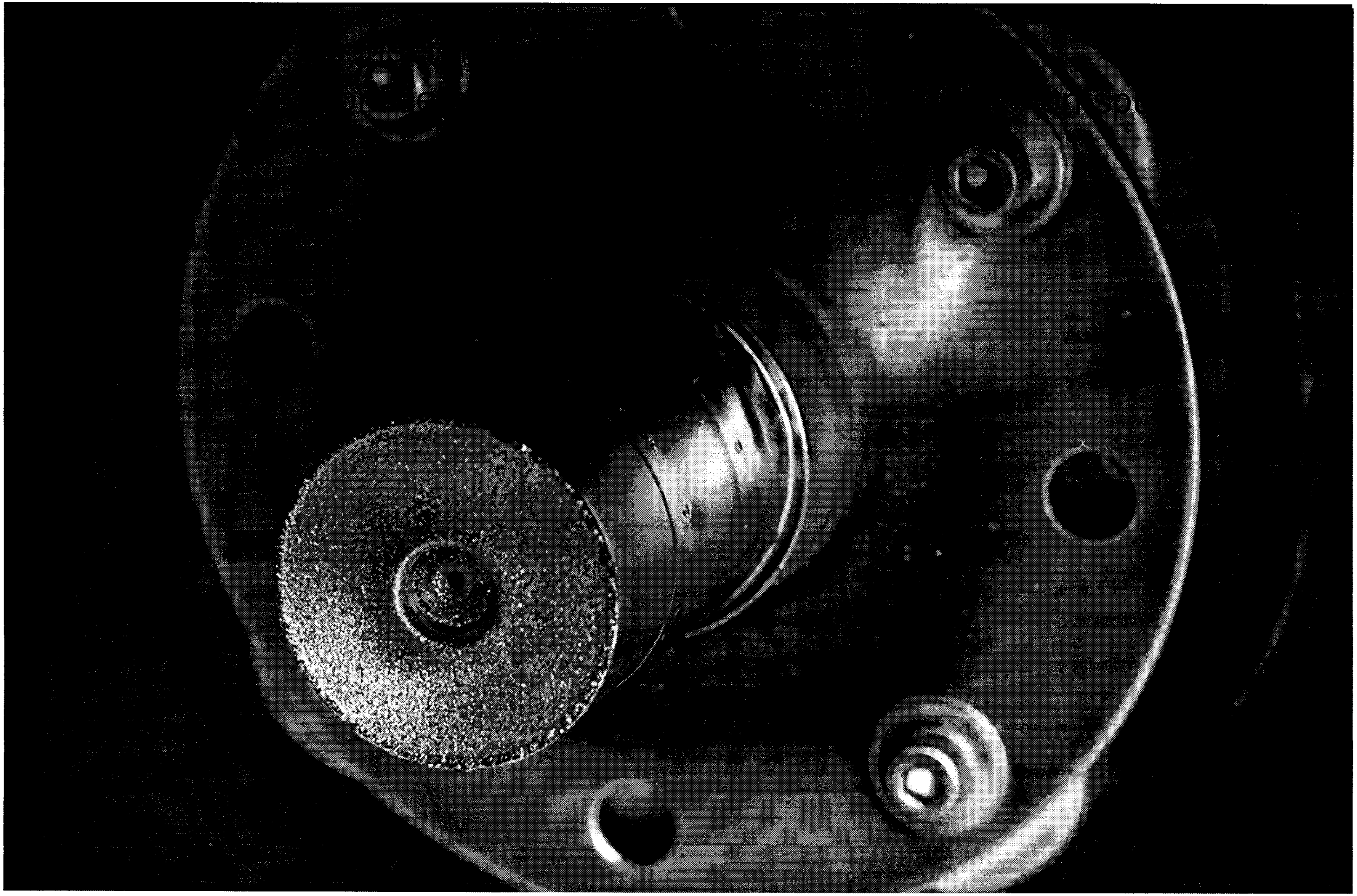


MESH 10:00

- **Belt and Suspenders Approach**
  - Sputter-containment mesh will retain flakes up to 30 µm in thickness
  - Don't expect a deposition thickness greater than approximately 15 µm after a throughput of 130 kg at full power resulting in a factor of 2 margin until flakes are expected
  - Most of the deposited molybdenum originates from the erosion of the accelerator grid apertures which decreases with throttle level.
  - Grid clear circuit capable of clearing a molybdenum wire 50 µm in diameter

NSTAR

Failure Modes 5 & 7 Main Cathode is in Excellent Condition After the 8.2-khr Test



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Failure Mode 5
Cathode Insert Life

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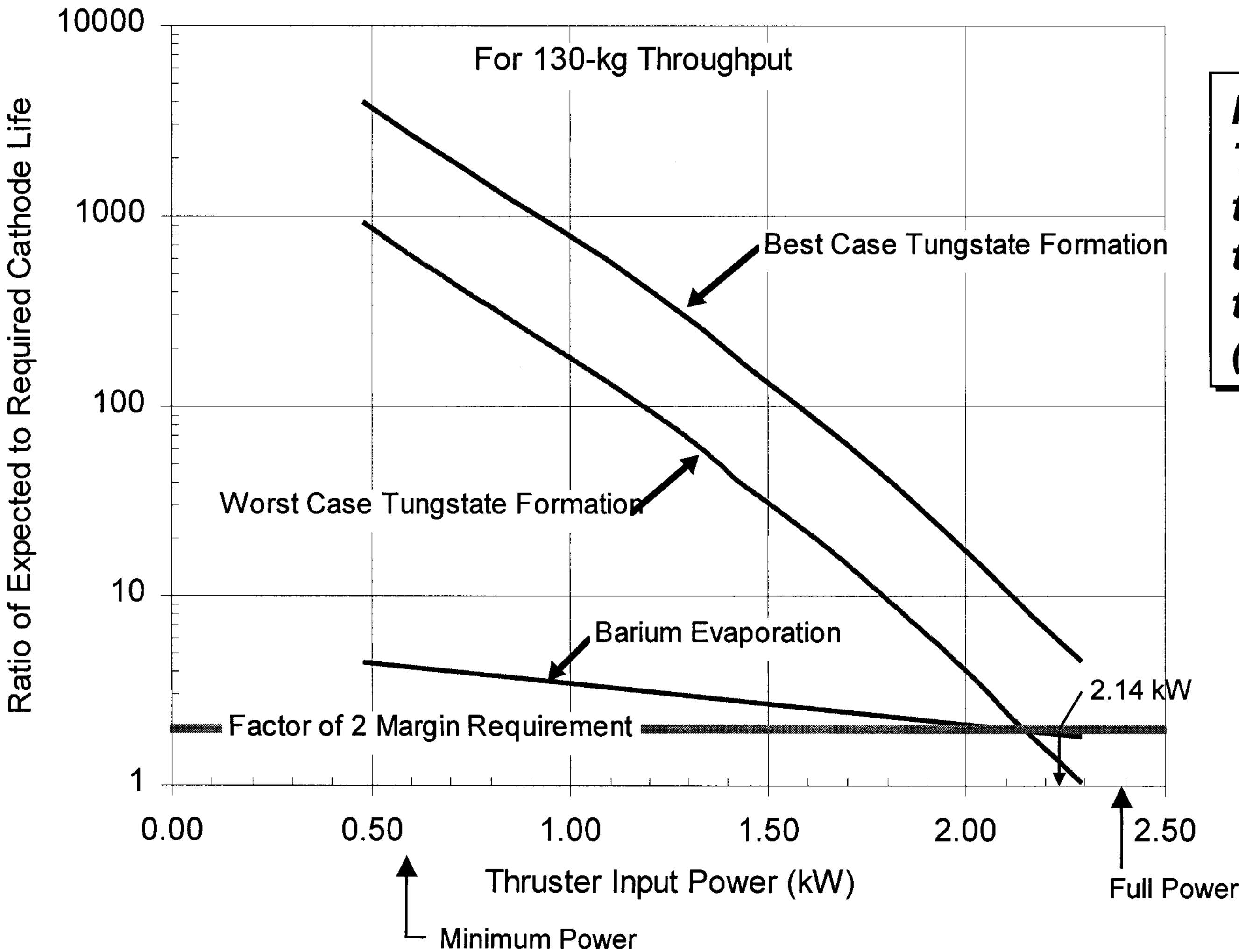
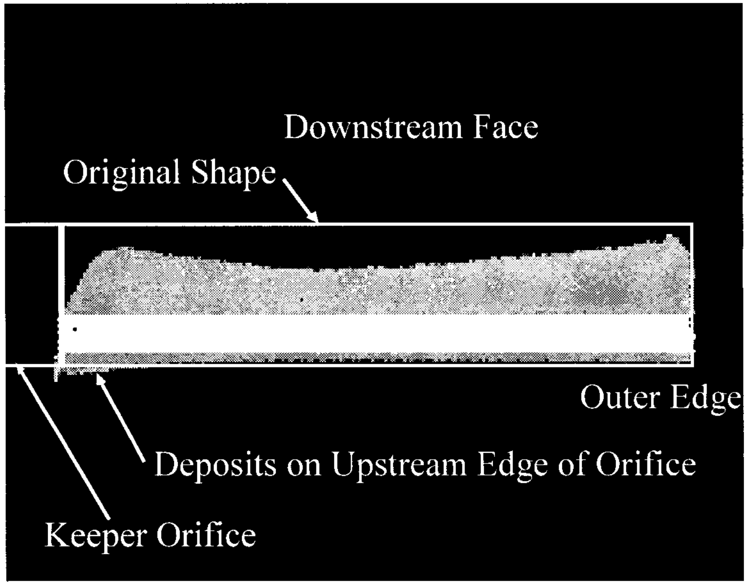
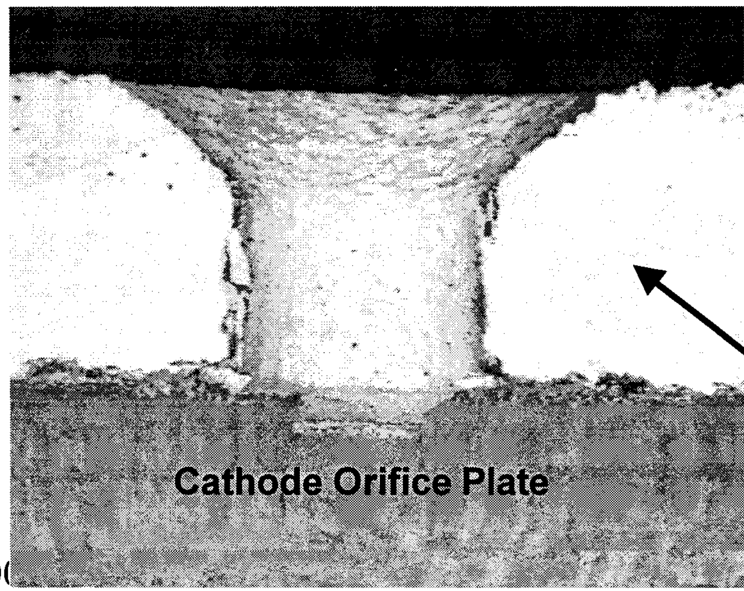
⑤ Cathode insert failure



Margin for 130-kg Throughput is greater than a factor of 2 provided the average engine throttle level is < 2.14 kW (93% of full power)

Failure Mode 7
Erosion on the Discharge Cathode Assembly Occurs Only on the Keeper Plate

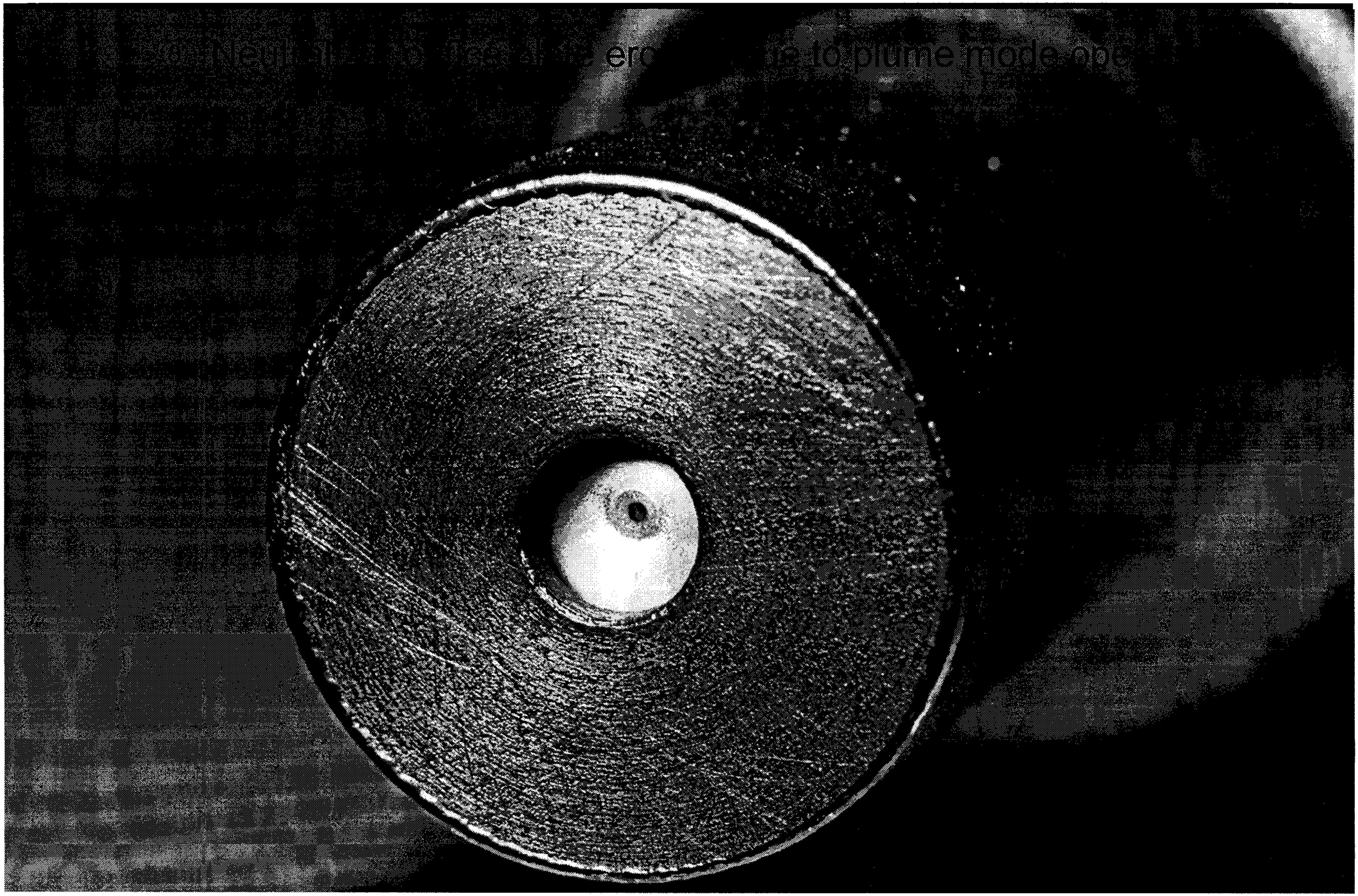




- **Discharge keeper plate wear:**
  - Plate Thinning (34% ± 2% of the original thickness was eroded) after 88-kg throughput
    - Linear extrapolation would result in erosion through ~51% of the plate thickness after a throughput of 130 kg
  - Deposits on upstream surfaces (up to 50 μm thick)
  - Slight wear on the keeper-plate to keeper-tube weld
  - Increase keeper plate thickness from 1.5 mm to 2.0 mm to provide factor of 2.6 margin at a throughput of 130 kg
- **Discharge cathode orifice plate shows *virtually no erosion***

NSTAR

Failure Mode 8
Neutralizer is in Excellent Condition After the 8.2-khr Test



NSTAR

Failure Mode 8
Neutralizer Cathode

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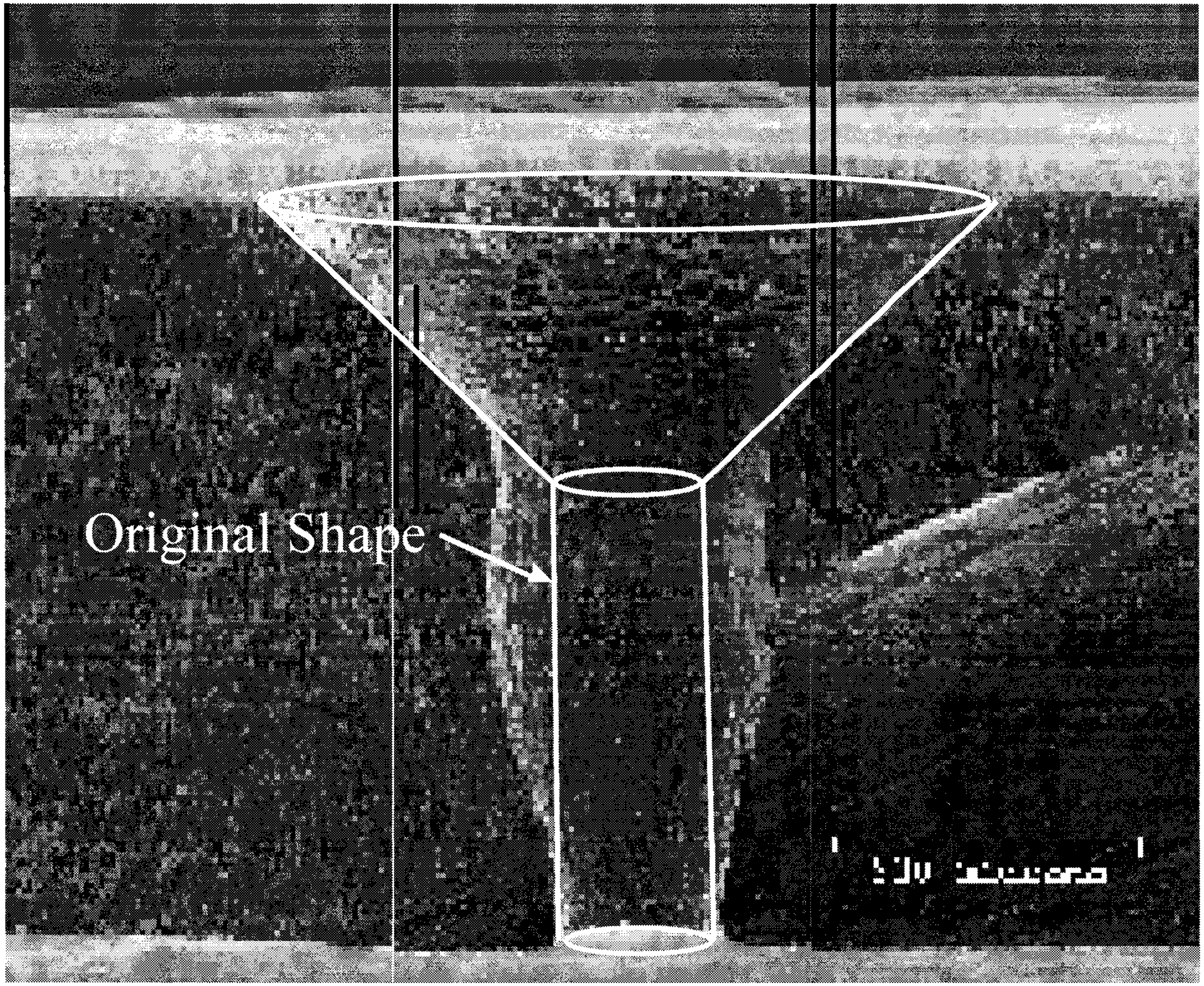
Wear Observed in the Orifice Only, But Very Little Change in Characteristics Over the Last 6,000 hours of the Test Suggest That This is the Steady-State Geometry



Service Life Summary

Failure Mode	Margin for 130-kg Throughput	Comment
1. Electron-Backstreaming	210%	10% failure risk at a throughput of 410 kg
2. Accelerator Grid Structural Failure	210%	10% failure risk at a throughput of 410 kg
3. Screen Grid Structural Failure	170%	10% failure risk at a throughput of 350 kg
4. Screen/Accelerator Grid Short (unclearable)	100%	In flake thickness
5. Cathode Insert Failure	> 100%	Provided the average engine throttle level is less than or equal to 2.14 kW
6. Rogue Hole Formation From Flakes	100%	in flake thickness
7. Keeper Orifice Plate Structural Failure	160%	After increasing the keeper plate thickness for 1.5 mm to 2.0 mm
8. Neutralizer Orifice Plate Erosion	unknown (but not a credible failure mode)	Operational constraint on neutralizer flow to stay in the spot mode
9. Cathode Heater Failure ($\leq$1000 cycles required)	570%	10% failure risk after 6680 on/off cycles (based on Space Station plasma contactor data)
10. Cathode/Keeper Short	unknown	Soft failure

- *Existing NSTAR Program Will Demonstrate 125-kg Throughput by the End of this Year*
- *Deep Space Exploration Focused Technology Program Will Extend this Test to > 200 kg Throughput by Jan. 2002*

NSTAR Risks Retired by the Flight on DS1

- Guidance, Navigation and Control of an SEP spacecraft is not more difficult with an SEP spacecraft, just different

- Mission Operations Costs -- the electrical nature of SEP lends itself well to autonomous operation resulting in essentially no significant increase in mission operations cost for SEP vehicles

- Contamination of the spacecraft by the SEP system can easily be handled through proper design

- Science Measurements of the solar wind can be made even during SEP operation

- Communications -- No impact of the SEP system could be detected

- Electromagnetic compatibility of the SEP system with the spacecraft requires careful engineering, but is easily tractable

Conclusions

- **NSTAR based SEP is a flight-validated technology**

- **With the NSTAR design and an operational scenario in which the average engine throttle level is less than 2.14 kW, the NSTAR ion engine is good for a throughput of 130 kg**

  - Outbound SEP missions will naturally have average power levels less than 2.14 kW (CNSR, for example, is 1.84 kW)

  - Operation of multiple engines simultaneously is expected to have no significant impact on the engine life